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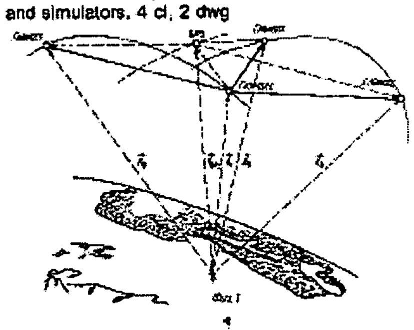
(54) RANGE-FINDING METHOD OF LOCATION AND COMPONENTS OF VECTOR OF VELOCITY OF OBJECTS BY RADIO SIGNALS OF SPACECRAFT OF SATELLITE RADIO NAVIGATION SYSTEMS

(57) Abstract:
FIELD: space radio navigation and geodesy. SUBSTANCE: navigation radio signals of satellites are received by N-channel receiver mounted on object, range from object to each satellite is found by measurement of time shifts of code sequences formed by satellite generators with regard to code sequence formed by object generators and of components of vector of velocity and by measurement of received Doppler shifts of frequency with use of systems tracking carriers. N-channel receiver has one driving channel and several driven channels, it determines difference between ranges measured by driven receiving channels and range measured by driving channel. It also determines difference of rates of change of ranges between rates of change of ranges computed by measurements of Doppler shifts of frequency by driven channels and rate of change of range computed by change of Doppler shift of frequency by driving receiving channel. Then determination of double differences of ranges and double differences of rates of change of ranges is conducted by way of mutual subtraction of differences of ranges and differences of rates of change of ranges. EFFECT: increased accuracy of determination of coordinates of position, components of vector of velocity of determined object by navigation signals of spacecraft of satellite radio navigation systems, with use of radio signals of ground and air radiation sources and with use of radiations of spacecraft of other systems and simulators. 4 cl, 2 dwg



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The invention relates to the field of space radio navigation and geodesy, and may be used for determining positional coordinates and components of the velocity vector of objects.

From *Shipboard satellite navigation complexes, by* P.S. Volosov, Y. S. Dubenko et al., Leningrad: Sudostroyenie Press, 1976, a Doppler difference range finder method is known for determining positional coordinates and components of the velocity vector of objects according to navigation radio signals of spacecraft in satellite radio navigation systems (SRNS) based on measurements of the differences of topocentric distances between the object and two positions of one and the same navigation spacecraft (NSC) into sequential moments of time.

The practical implementation of the known method is the Russian Tsikada SRNS and the American Transit SRNS, which are first-generation navigation systems. In it, integration of the Doppler shift of radio signals received over a time interval ΔT from an artificial earth navigation satellite (AENS) permits determination of the number of wavelengths being stacked at a variety of distances from the phase center of the antenna of the object's receiver up to two AENS positions (two positions of the phase center of the AENS antenna):

$$\Delta R = \int_{t_1+\frac{R_1(t_1)}{c}}^{t_2+\frac{R_2(t)}{c}} F_A(t)\cdot dt = \int_{t_1+\frac{R_1(t_1)}{c}}^{t_2+\frac{R_2(t_2)}{c}} (f_o-f_n)dt =$$

$$= (f_o-f_n)\cdot(t_2-t_1) + \frac{f_o}{c}[R_2(t_2)-R_1(t_1)].$$

where

t_1 and t_2 are the transmission time of the AENS time mark

$R_1(t_1)$ and $R_2(t_2)$ are the distances between phase centers of the antennas of the object and AENS

c is the speed of light

f_n is the received signal frequency

f_o is the reference signal frequency

$F_п = f_и \pm \Delta f_и + \Delta f_{ио} + \Delta f_{тр} + \Delta f_{гр} + \Delta f_{др}$, where

$f_и$ is the frequency of the signal emitted by the AENS

$\pm \Delta f_и$ is the frequency instability of the emitted signal;

$\Delta f_{ио}$, $\Delta f_{тр}$ are the unknown phase shifts caused by propagation of signals in the ionosphere and troposphere

$\Delta f_{гр}$ is the unknown phase shift caused by gravitational forces

$\Delta f_{др}$ are the unknown phase shifts caused by other factors

$f_o = f_и \pm \Delta f + \Delta f_o$

where

Δf_o is the known constant phase shift (frequency standard)

$\pm \Delta f$ is the frequency instability of the reference signal.

Allowing for what has been presented, the expression takes the form

$$\Delta R = [(f_и \pm \Delta f + \Delta f_o) - (f_и \pm \Delta f_и + \Delta f_{ио} + \Delta f_{тр} + \Delta f_{гр} +$$

$$+ \Delta f_{др})]\cdot(t_2-t_1) + \frac{f_o}{c}[R_2(t_2)-R_1(t_1)].$$

From the expression it is evident that the integral Doppler shift is determined by two terms. The first term is the measurement error caused by conditions for radio wave propagation, the Earth's gravitational field, the frequency instability of reference generator emission, and other factors. They will become part of the navigation equation as unknowns. The second term is a direct measurement of the change in the range inclination in wavelengths of the reference frequency of the object being detected.

The term error of the system for tracking the carrier (STC), which is lacking in the navigation equation under consideration, also enters into the measurement error of the radio navigation parameter (RNP). The time function being tracked – the carrier frequency – has non-zero high order derivatives. Consequently, along with random (noise) errors, the actual tracking contour with astatism of a finite order will have dynamic errors caused by the presence of input-action derivatives of a higher order than the order of system astatism. Reducing random errors in an automatic frequency control system (AFCS) requires application of a more inertial feedback contour with narrowing of the low-frequency bandpass filter transmission band. With this, however the STC dynamic errors increase, and vice versa.

Expressing range through coordinates of a rectangular geocentric coordinate system, the navigation equation will assume the form

$$\Delta R = [(x_2-x_0)^2+(y_2-y_0)^2+(z_2-z_0)^2]^{1/2} -$$

$$-[(x_1-x_0)^2+(y_1-y_0)^2+(z_1-z_0)^2]^{1/2},$$

where

x_1, y_1, z_1, x_2, y_2, z_2 are coordinates of the phase center of the satellite antenna at the moments of time t_2 and t_1 respectively;

x_0, y_0 and z_0 are unknown coordinates of the phase center of the antenna of the object being determined.

As is evident, three measurements of range difference in four sequential positions of the satellite in the orbit permit coordinates of the object x_0, y_0 and z_0 to be determined. In the process of the measurements, we must wait until the range to the AENS changes by a sufficient amount.

The range difference method reveals its distinctions at such distances (bases) between AENS positions in orbit, when they are commensurate with distances with distances between navigation satellites and the object being detected.

According to the presented inadequate features of the known method, there are

errors caused by the STC;

errors due to frequency instability of emission from the navigation satellite and the reference generator;

errors caused by conditions for propagation of radio waves in the ionosphere and troposphere and other factors;

systematic and random errors;

low precision in determining locational coordinates and components of the velocity vector of objects when using AENS at medium-high and high orbits.

Also known is a range-finding method that is employed as a prototype. The practical implementation of this method is a second-generation SRNS, the Russian Global Orbiting Navigation Satellite System (GLONASS) and the American Global Positioning System (GPS). The geometric equivalent of the final algorithm of this method for solving the navigation problem, regarding the artificial earth navigation satellites (AENS), is to construct a totality of positional surfaces, the point of intersection of which is the desired position of the object (*On-board devices for satellite radio navigation*, under the editorship of V. S. Shebshayevich; Moscow, Transport Press, 1988).

To solve the navigation problem, the minimum necessary quantity of functional dependencies must be equal to the number of parameters under assessment. Determining the positional coordinates of the object is reduced to solving the system of equations

$$R_1=[(x_1-x)^2+(y_1-y)^2+(z_1-z)^2]^{1/2}+\Delta R_T+\Delta R_1;$$
$$R_2=[(x_2-x)^2+(y_2-y)^2+(z_2-z)^2]^{1/2}+\Delta R_T+\Delta R_2;$$
$$R_3=[(x_3-x)^2+(y_3-y)^2+(z_3-z)^2]^{1/2}+\Delta R_T+\Delta R_3;$$
$$R_4=[(x_4-x)^2+(y_4-y)^2+(z_4-z)^2]^{1/2}+\Delta R_T+\Delta R_4,$$

where

$R_1, \ldots, R_4$ are the results of measurements of range inclinations obtained with the aid of the delay tracking system (DTS):

x, y, z are object coordinates in a geometric rectangular coordinate system;

x_1, y_1, z_1 ..... x_4, y_4, z_4 are coordinates of four satellites transmitted in the navigation message;

ΔR_T is the difference between the true satellite-to-object range and that measured, caused by a shift in the object's time scale relative to the time scale of the AENS;

ΔR_1 ..... ΔR_4 are the measurement errors caused by the atmosphere, ionosphere and other factors.

To determine the object's positional coordinates, it is necessary that simultaneously four satellites be found in the object's field of vision. As a result of solving this system of equations, four known quantities are determined: three coordinates of the object location (x, y, z) and a correction ΔR_T to its time scale (correction to hours).

In analogous fashion, with use of the measurement results aided by the satellite navigation system, three components are determined of the velocity vector $\dot{x}, \dot{y}, \dot{z}$ and the correction $\Delta\dot{R}_T$ to the frequency of the standard for the object frequency, used to form the time scale:

$$\dot{R}_1=R_1^{-1}[(x_1-x)\cdot(\dot{x}_1-\dot{x})+(y_1-y)\cdot(\dot{y}_1-\dot{y})+$$
$$+(z_1-z)(\dot{z}_1-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}_1;$$
$$\dot{R}_2=R_2^{-1}[(x_2-x)\cdot(\dot{x}_2-\dot{x})+(y_2-y)\cdot(\dot{y}_2-\dot{y})+$$
$$+(z_2-z)(\dot{z}_2-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}_2;$$
$$\dot{R}_3=R_3^{-1}[(x_3-x)\cdot(\dot{x}_3-\dot{x})+(y_3-y)\cdot(\dot{y}_3-\dot{y})+$$
$$+(z_3-z)(\dot{z}_3-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}_3;$$
$$\dot{R}_4=R_4^{-1}[(x_4-x)\cdot(\dot{x}_4-\dot{x})+(y_4-y)\cdot(\dot{y}_4-\dot{y})+$$
$$+(z_4-z)(\dot{z}_4-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}_4$$

where

$\Delta\dot{R}_1, \ldots, \Delta\dot{R}_4$ is the range alteration rate (radial velocities) measured with the aid of the satellite navigation system;

$\dot{x}, \dot{y}, \dot{z}$ are components of the object's velocity vector;

$\dot{x}_1, \dot{y}_1, \dot{z}_1$ ... $\dot{x}_4, \dot{y}_4, \dot{z}_4$ are components of the vector of the velocity of the four satellites;

$\Delta\dot{R}_T$ is the difference between the true velocity and the measured one, caused by a divergence of the frequencies of the frequency standards of the AENS and object;

$\Delta\dot{R}_1, \ldots, \Delta\dot{R}_4$ are the measurement errors caused by radio wave propagation conditions and other factors.

Range is measured in the object's apparatus by measuring the time interval between the time marks of the code received from the satellite and the object's local code.

The effectiveness of this method is determined mainly by the noise error of RNP measurement, since it is just the noise error that limits the compensation effect of strongly correlated errors. Citing from *On-board devices for satellite radio navigation*, under the editorship of V. S. Shebshayevich; Moscow, Transport Press, 1988), for assessment of the noise error, we employ the expression

$$\varepsilon_{ш}^2 = \Delta\left[\frac{K_1 \Delta B_{CC3}}{c/N_0} + \frac{K_2 \Delta B_{ПЧ} \Delta B_{CC3}}{c/N_0^2}\right],$$

where

$\varepsilon_{ш}^2$ is the dispersion of measurement noise;

Δ is the length of an element of the range finding code;

c/N_0 is the relation of the signal strength to the spectral density of noise strength at the input of the receiver;

ΔB_{CC3} is the unilateral width of the DTS band;

$\Delta B_{ПЧ}$ is the unilateral bandwidth of the UPCh discriminator; and K_1, K_2 are the constant parameters dependent on the technical solution chosen.

Measurement of the Doppler shift is based on measurement of the range increment at the carrier frequency, using a satellite navigation system.

Assessment of the precision of range increment measurement is determined by an expression for phase dispersion $\varepsilon_{Ф}^2$ of a scheme for tracking the carrier, having the form

$$\varepsilon_{Ф}^2 = \frac{\lambda^2 B_{CCH}}{(2\pi)^2 c/N_0},$$

where

λ is the wavelength of the carrier;

B_{CCH} is the bandwidth of the scheme for tracking the carrier.

The noise error in measurements of range increments at the carrier frequency is practically an order lower than the noise error of range measurements using range finding codes.

Due to differences in, for example, GLONASS and GPS systems for satellite radio navigation, the range finding method does not permit them to be used in concert.

Thus, the inadequacies of the known method, the prototype, are:

errors in the system for tracking of time lag from the signal-to-noise ratio;

errors in the system for tracking the carrier from the signal-to-noise ratio;

errors caused by radio wave propagation conditions in the ionosphere and troposphere and other factors;

errors caused by a time scale shift of the object relative to the time scale of the AENS due to frequency instability of satellite generators and the object's reference generator;

the impossibility of making joint use of radio emission sources in systems having different assignments.

To eliminate the ionospheric lag in known methods, use is made of apparatus compensation using dual-frequency measurements and of compensation employing corrections computed according to a priori data.

The known prototype method is characterized by the following totality of actions on received satellite radio navigation signals:

reception by an N-channel receiver of dual-frequency radio signals N of an AENS;

determination of the range from the object to each satellite by measuring the time shifts of code sequences being formed by satellite generators relative to code sequences being formed by the object's generator;

measurement of the range increment via measurement of the increments of carrier phases;

determination of the coordinates of object position;

determination of the components of the object's velocity vector.

The purpose of the invention is to increase accuracy in determining positional coordinates, components of the velocity vector of the object being detected according to SRNS spacecraft radio signals of ground air sources of radio emission, and also using the radio emission of satellites from other systems and their simulators.

This goal is achieved in that, according to the proposed method, in an N-channel receiver, one of which is the driving one, and the others are the driven channels, the range difference is determined between ranges measured by driven receivers and the range measured by the driving receiver, and also a determination of the velocity differences of range changes between range change velocities computed as per changes in the Doppler shifts by driven receivers, and the range change velocity computed as per changes in the Doppler shift by the driving receiver, then determining the dual differences of range and the dual differences of range change velocity by means of mutual subtraction from each other of range differences and differences in the range change velocities.

The additional distinctive features of the proposed method are the following.

Via the driving and receiving devices the range differences between the object and two satellite positions are determined by a measured interval by measuring the phase increment of the carrier using automatic frequency controls of systems for tracking the carrier navigation radio signals of satellites.

The dual range differences between the object and two satellite positions are determined by a measured interval, using measurement of Doppler shifts detected by receivers using quadrature phase detectors after multiplying their mean values by the measured interval.

The driving-channel receiver receives signals of a simulator of satellite signals.

The signals with Doppler frequencies are separated by squaring the received signals, subsequently returning the frequencies to the desired ones using frequency dividers.

The geometric interpretation of the proposed method is explained using the example of a constellation of four GLONASS satellites and one GPS satellite in figure 1.

The GPS satellite radio signal detected by the receiver is the driving signal, and the channel for reception of the GLONASS satellite receiver is the driven one. Accordingly, the navigation signals of the GLONASS satellite, and the satellite receiver, are the driven ones.

In accordance with what is presented above,

$$\begin{aligned}
\Delta\vec{R}_1 &= \vec{R}_1-\vec{R}_{GPS};\\
\Delta\vec{R}_2 &= \vec{R}_2-\vec{R}_{GPS};\\
\Delta\vec{R}_3 &= \vec{R}_3-\vec{R}_{GPS};\\
\Delta\vec{R}_4 &= \vec{R}_4-\vec{R}_{GPS};\\
\Delta\Delta\vec{R}_{2,1} &= \Delta\vec{R}_2-\Delta\vec{R}_1=(\vec{R}_2-\vec{R}_{GPS})-(\vec{R}_1-\vec{R}_{GPS}) = \vec{R}_2-\vec{R}_1;\\
\Delta\Delta\vec{R}_{3,1} &= \Delta\vec{R}_3-\Delta\vec{R}_1=(\vec{R}_3-\vec{R}_{GPS})-(\vec{R}_1-\vec{R}_{GPS}) = \vec{R}_3-\vec{R}_1;\\
\Delta\Delta\vec{R}_{4,1} &= \Delta\vec{R}_4-\Delta\vec{R}_1=(\vec{R}_4-\vec{R}_{GPS})-(\vec{R}_1-\vec{R}_{GPS}) = \vec{R}_4-\vec{R}_1;
\end{aligned} \tag{1}$$

where

$\Delta\vec{R}_1, \Delta\vec{R}_2$ is the difference of the measured

$\Delta\vec{R}_3, \Delta\vec{R}_4$

of ranges between each driven GLONASS satellite user and between the driving GPS satellite user employing range finding codes;

$\Delta\Delta\vec{R}_{2,1}; \Delta\Delta\vec{R}_{3,1}; \Delta\Delta\vec{R}_{4,1}$ are dual range differences.

The geometric interpretation of determining coordinates and velocity vector components according to differences in range increments and the dual increment differences measured using increments of the carrier phases, is explained using the example of two satellites: a driving satellite and a driven GLONASS satellite, in figure 2.

The points t_1, t^*, t_2 indicate positions of the AENS in the orbit, which are limits of navigation parameter readings (the measured interval).

The differences of range increments are written in the following manner consequently:

$$\Delta\Delta\vec{R}_1 = [\vec{R}_1(t_2)-\vec{R}_1(t_1)]-[\vec{R}_{GPS}(t_2)-\vec{R}_{GPS}(t_1)];$$

$$\Delta\Delta\vec{R}_2 = [\vec{R}_2(t_2)-\vec{R}_2(t_1)]-[\vec{R}_{GPS}(t_2)-\vec{R}_{GPS}(t_1)];$$

$$\Delta\Delta\vec{R}_3 = [\vec{R}_3(t_2)-\vec{R}_3(t_1)]-[\vec{R}_{GPS}(t_2)-\vec{R}_{GPS}(t_1)];$$

$$\Delta\Delta\vec{R}_4 = [\vec{R}_4(t_2)-\vec{R}_4(t_1)]-[\vec{R}_{GPS}(t_2)-\vec{R}_{GPS}(t_1)].$$

The dual range increment differences will take the form

$$\Delta\Delta\Delta\vec{R}_{2,1} = \Delta\Delta\vec{R}_2-\Delta\Delta\vec{R}_1 = [\vec{R}_2(t_2)-\vec{R}_2(t_1)]-$$
$$-[\vec{R}_1(t_2)-\vec{R}_1(t_1)];$$

$$\Delta\Delta\Delta\vec{R}_{3,1} = \Delta\Delta\vec{R}_3-\Delta\Delta\vec{R}_1 = [\vec{R}_3(t_2)-\vec{R}_3(t_1)]-$$
$$-[\vec{R}_1(t_2)-\vec{R}_1(t_1)];$$

$$\Delta\Delta\Delta\vec{R}_{4,1} = \Delta\Delta\vec{R}_4-\Delta\Delta\vec{R}_1 = [\vec{R}_4(t_2)-\vec{R}_4(t_1)]-$$
$$-[\vec{R}_1(t_2)-\vec{R}_1(t_1)]. \qquad (2)$$

The range differences in square brackets of equation system (1) manifest their distinctive features, as was shown above at such distances (bases) between AENS positions in orbit when they are commensurate with the distance between a navigation satellite and the object to be detected. In our example, the bases are insignificant. To comply with this condition, equation system (2) is transformed into an identical system of equations in which this condition is implemented:

$$\Delta\Delta\Delta\vec{R}_{2,1} = [\vec{R}_2(t_2)-\vec{R}_1(t_2)]-[\vec{R}_2(t_1)-\vec{R}_1(t_1)];$$

$$\Delta\Delta\Delta\vec{R}_{3,1} = [\vec{R}_3(t_2)-\vec{R}_1(t_2)]-[\vec{R}_3(t_1)-\vec{R}_1(t_1)];$$

$$\Delta\Delta\Delta\vec{R}_{4,1} = [\vec{R}_4(t_2)-\vec{R}_1(t_2)]-[(\vec{R}_4(t_1)-\vec{R}_1(t_1)]. \qquad (3)$$

Thus, from the system of range differences for the navigation satellite orbit with identical orbit parameters for the constellation of 5 navigation satellites, the one GPS is the driving one, and the four GLONASS ones are driven.

The final system of equations for dual range differences (1) and for dual differences in range increments (3), expressed through coordinates in a geometric rectangular coordinate system will take the form

for dual range differences

$$\Delta\Delta\vec{R}_{2,1} = \vec{R}_2-\vec{R}_1 = [(x_2-x)^2+(y_2-y)^2+(z_2-z)^2]^{1/2}+$$
$$+\Delta R_T+\Delta R_2-[(x_1-x)^2+(y_1-y)^2+(z_1-z)^2]^{1/2}-\Delta R_T-\Delta R_1;$$

$$\Delta\Delta\vec{R}_{3,1} = \vec{R}_3-\vec{R}_1 = [(x_3-x)^2+(y_3-y)^2+(z_3-z)^2]^{1/2}+$$
$$+\Delta R_T+\Delta R_3-[(x_1-x)^2+(y_1-y)^2+(z_1-z)^2]^{1/2}-\Delta R_T-\Delta R_1;$$

$$\Delta\Delta\vec{R}_{4,1} = \vec{R}_4-\vec{R}_1 = [(x_4-x)^2+(y_4-y)^2+(z_4-z)^2]^{1/2}+$$
$$+\Delta R_T+\Delta R_4-[(x_1-x)^2+(y_1-y)^2+(z_1-z)^2]^{1/2}-\Delta R_T-\Delta R''_1; \qquad (4)$$

For dual differences in range increments

$$\Delta\Delta\Delta\vec{R}_{2,1} = [(x''_2-x)^2+(y''_2-y)^2+(z''_2-z)^2]^{1/2}+$$
$$+\Delta R_T+\Delta R''_2-[(x''_1-x)^2+(y''_1-y)^2+(z''_1-z)^2]^{1/2}-\Delta R_T-\Delta R''_1-$$
$$-[(x'_2-x)^2+(y'_2-y)^2+(z'_2-z)^2]^{1/2}-\Delta R_T-\Delta R'_2+$$
$$+[(x'_1-x)^2+(y'_1-y)^2+(z'_1-z)^2]^{1/2}+\Delta R_T-\Delta R'_1;$$

$\vdots$

$$\Delta\Delta\Delta\vec{R}_{3,1} = [(x''_3-x)^2+(y''_3-y)^2+(z''_3-z)^2]^{1/2}+$$
$$+\Delta R_T+\Delta R''_3-[(x''_1-x)^2+(y''_1-y)^2+(z''_2-x)^2]^{1/2}-\Delta R_T-\Delta R''_1-$$
$$-[(x'_3-x)^2+(y'_3-y)^2+(z'_3-z_1)^2]^{1/2}-\Delta R_T-\Delta R'_3+$$
$$+[(x'_1-x)^2+(y'_1-y)^2+(z'_1-z)^2]^{1/2}+\Delta R_T-\Delta R'_1;$$

$\vdots$

$$\Delta\Delta\Delta\vec{R}_{4,1}[(x''_4-x)^2+(y''_4-y)^2+(z''_4-z)^2]^{1/2}+$$
$$+\Delta R_T+\Delta R''_4-[(x''_1-x)^2+(y''_1-y)^2+(z''_1-z)^2]^{1/2}-$$
$$-\Delta R_T-\Delta R''_1-[(x'_4-x)^2+(y'_1-y)^2+(z'_1-z)^2]^{1/2}-$$
$$-\Delta R_T-\Delta R'_4+[(x'_1-x)^2+(y'_1-y)^2+(z'_1-z)^2]^{1/2}+$$
$$+\Delta R_T+\Delta R'_1, \qquad (5)$$

where

x'_1, x''_1, y'_1, y''_1, z'_1, z''_1 are coordinates

. . . .

. . . .

x'_4, x''_4, y'_4, y''_4, z'_4, z''_4

of driven AENS, transmitted in navigation messages at the moments of time t_1 and t_2 respectively.

Similarly, with the use of results from measurements using satellite navigation systems, the components of the velocity vector are determined:

$$
\begin{aligned}
\Delta\Delta\Delta\dot{R}_{2,1} = {} & \dot{R}^{-1}_{2,1}(t_2)\cdot\{[(x''_2-x)\cdot(\dot{x}''_2-\dot{x})+(y''_2-y)\times \\
& \times(\dot{y}''_2-\dot{y})+(z''_2-z)\cdot(\dot{z}''_2-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}''_2]-[(x''_1-x)\times \\
& \times(\dot{x}''_1-\dot{x})+(y''_1-y)\cdot(\dot{y}''_1-\dot{y})+(z''_1-z)\cdot(\dot{z}''_1-\dot{z})-\Delta\dot{R}_T-\Delta\dot{R}''_1]\} - \\
& -\Delta\dot{R}^{-1}_{2,1}(t_1)\cdot\{[(x'_2-x)\cdot(\dot{x}_2-\dot{x})+(y'_2-y)\cdot(\dot{y}_2-\dot{y})+ \\
& +(z'_1-z)\cdot(\dot{z}'_2-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}'_2]-[(x'_1-x)\cdot(\dot{x}'_1-\dot{x})+ \\
& +(y'_1-y)\cdot(\dot{y}'_1-\dot{y})+(z'_1-z)\cdot(\dot{z}'_1-\dot{z})-\Delta R_T-\Delta\dot{R}'_1]\} \;;
\end{aligned}
$$

$\vdots$

$$
\begin{aligned}
\Delta\Delta\Delta R_{3,1} = {} & \dot{R}^{-1}_{3,1}(t_2)\cdot\{[(x''_3-x)\cdot(\dot{x}''_3-\dot{x})+(y''_3-y)\times \\
& \times(\dot{y}''_3-\dot{y})+(z''_3-z)\cdot(\dot{z}''_3-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}''_3]-[(x''_1-x)\times \\
& \times(\dot{x}''_1-\dot{x})+(y''_1-y)\cdot(\dot{y}''_1-\dot{y})+(z''_1-z)\cdot(\dot{z}''_1-\dot{z})-\Delta\dot{R}_T-\Delta\dot{R}''_1]\} - \\
& -\Delta R^{-1}_{3,1}(t_1)\cdot\{[(x'_3-x)\cdot(\dot{x}'_3-\dot{x})+(y'_3-y)\cdot(\dot{y}'_3-\dot{y})+ \\
& +(z'_3-z)\cdot(\dot{z}'_3-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}'_3]-[(x'_1-x)\cdot(\dot{x}'_1-\dot{x})+ \\
& +(y'_1-y)\cdot(\dot{y}'_1-\dot{y})+(z'_1-z)\cdot(\dot{z}'_1-\dot{z})-\Delta R_T-\Delta\dot{R}'_1]\} \;;
\end{aligned}
$$

$\vdots$

$$
\begin{aligned}
\Delta\Delta\Delta\dot{R}_{4,1} = {} & \dot{R}^{-1}_{4,1}(t_2)\cdot\{[(x''_4-x)\cdot(\dot{x}''_4-\dot{x})+(y''_4-y)\times \\
& \times(\dot{y}''_4-\dot{y})+(z''_4-z)\cdot(\dot{z}''_4-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}''_3]-[(x''_1-x)\times \\
& \times(\dot{x}''_1-\dot{x})+(y''_1-y)\cdot(\dot{y}''_1-\dot{y})+(z''_1-z)\cdot(\dot{z}''_1-\dot{z})-\Delta\dot{R}_T-\Delta\dot{R}''_1]\} - \\
& -\Delta R^{-1}_{4,1}(t_1)\cdot\{[(x'_4-x)\cdot(\dot{x}'_4-\dot{x})+(y'_4-y)\cdot(\dot{y}'_4-\dot{y})+ \\
& +(z'_4-z)\cdot(\dot{z}'_4-\dot{z})+\Delta\dot{R}_T+\Delta\dot{R}'_4]-[(x'_1-x)\cdot(\dot{x}'_1-\dot{x})+ \\
& +(y'_1-y)\cdot(\dot{y}'_1-\dot{y})+(z'_1-z)\cdot(\dot{z}'_1-\dot{z})-\Delta R_T-\Delta\dot{R}'_1]\} \;;
\end{aligned}
\tag{6}
$$

where

$x'_1, x''_1, y'_1, y''_1, z'_1, z''_1$ are components

. . . .

. . . .

$x'_4, x''_4, y'_4, y''_4, z'_4, z''_4$

of the AENS velocity vector transmitted in navigation messages at moments of time t_1 and t_2 respectively.

It is evident in analyzing systems of navigation equations of dual range differences (4), dual differences in range increments (5) and velocity (6) with use of the driving and driven AENS radio signals and corresponding receivers and channels, that in the equations, the coordinates of the driving GPS AENS are compensated. Also compensated are the errors, caused by a divergence in the time scales and frequencies of GPS and GLONASS relative to the time scales and frequencies of the object.

If in the navigation equations of the known method there are errors caused by the ionosphere and troposphere, then their differences are present in equations of the proposed method using dual range differences.

To ensure a high-accuracy navigation task. depending on the geometric factor of determining the position in space, the satellite position in space is selected to be such that one satellite is at the zenith (ensuring high accuracy in determining the position along the vertical), which the remaining satellites are in a horizontal plane in directions that differ from each other by 120 - 180°, ensuring high accuracy in determining the position along the horizontal, depending on the number of satellites used.

Thus, the proposed method, despite, for example, serious differences between GLONASS and GPS, in methods of assigning ephemeredes, in the arrangement of super-settings of service information, in the fact that the systems for reporting special coordinates are not identical, and the difference in time scales formed from varying frequency and time standards, permits them to be used jointly, without making them conform as required, i.e., with no organizational material processing and processing of the mathematical system support.

In receiving radio navigation signals from the GLONASS and GPS satellites in parallel or sequentially, using a multiplex receiver or a multichannel one, and also having the GPS satellite be the driving one in one series of measurements and the GLONASS satellite as the driven one, and vice versa in another series, we can determine coordinates and velocity vector coordinates of the object in the GPS coordinate-time system or in the GLONASS coordinate-time system, without making them conform.

Joint use of the systems ensures a certain universality of navigation determinations, reliability and trustworthy observation due to determinations being compared in differing systems to reveal instances where one of the systems has a functional violation.

By navigational support reliability what is meant is the navigation system's capability at any moment in time to provide the object with

information to determine location with an accuracy guaranteed for the operational zone.

By authenticity what is meant is the navigation system's capability to reveal deviations in its functioning that lead to an impairment in accuracy of determining coordinates and components of the object's velocity vector going beyond the limits of the given permissible values.

If the system of dual-difference navigation equations of the proposed method, using measurements aided by range finding codes (1) is in essence a system of range difference equations, then the system of navigation equations of dual differences in range increments, measured with the aid of phase increments of the carrier at a measured interval (2) is a system of equations of dual range differences and also permits the navigation problem to be solved – to determine position coordinates and components of the object's velocity vector. Since, as was shown above, the measurement accuracy of phase increment differences at carrier frequencies is higher by an order than the accuracy of time shift difference measurements of code sequences, then the accuracy by which the navigation problem is solved using phase increments is also higher than the accuracy of the solution using range differences.

For purposes of further increasing the accuracy by which the navigation problem is solved using phase increments at carrier frequencies by eliminating errors from the measurements caused by satellite navigation systems, dual differences in range increments are produced by separation from received signals with frequencies equal to Doppler frequency differences using quadrature phase detectors, to the initial outputs of which a signal of the driving receiver arrives, and to the secondary outputs of which arrive signals of driven receiver. Then the differences in phase increments are determined by multiplying mean values of Doppler frequency differences by the measured interval and determining dual differences of phase increments by mutually subtracting them.

The information presented corresponds to the implementation in apparatus, a block diagram of which is presented in figure 3. Signals with Doppler frequencies are separated upon receipt of phase-modulated signals with suppressed carriers by squaring them, then filtering, with subsequent return of the frequencies to the desired ones using frequency dividers.

Signals from outputs of convolution devices which arrive in AFCS systems of satellite navigation systems of receivers in figure 3, in a synchronism mode by delays of range finding codes are significantly narrow-band signals - restored carriers, modulated by digital data. The ranges for changes in carrier values are determined mainly by the Doppler shift (≈ ± 50 kHz at frequencies of a GPS or GLONASS satellite), while the signal spectrum width is determined by the digital data spectrum (≈ 100 Hz).

AFCS signals can track signals corresponding to only one of the two side bands, and consequently, have energy losses equal to 3 dB. Therefore, connecting the device for separation from received navigation signals equal to the Doppler frequency differences of the proposed method of figure 3, excluding the secondary side bands, does not input additional energy losses.

The received and transformed satellite navigation radio signals arriving at quadrature phase detectors, already carry within themselves frequency shifts caused by generator instabilities of the spacecraft and object, caused by radio wave propagation conditions in the ionosphere and troposphere, shifts caused by the receiver paths, and other factors. Therefore, in the process of separating oscillations with frequencies equal to the Doppler frequency differences from the proposed method, the enumerated frequency deviations partially compensate for each other. And already with the tertiary differences their contribution to the accuracy of the navigation determinations will be insignificant.

When used for solving the navigation problem of phase increments, the influences of phase differences on the accuracy due to the ionosphere and troposphere for limiting points of the measured interval differ little, and when secondary differences are formed, they are virtually eliminated. A special distinguishing feature of the proposed method is that when measuring differences in phase increments with use of oscillations equal to Doppler frequency differences, the signal of any radiation source may be used as the driving signal, be it ground-based, air-based, or radiation from spacecraft of other systems. In this instance, the main requirement for the receiver of the object being detected is the capability to receive a signal and to transform it in such a way that it ensures that

the block of quadrature phase detectors functions will function. There is no need to know the coordinates of radiation sources, their time systems, frequency instability and frequency increments due to radio wave propagation. They are compensated for in the process of navigation measurements.

The most optimal version of device implementation of the proposed method is the version when carrier signals, modulated by range finding codes of the simulators are used as the driving signal of the object's receiver. Simulators permit optimization of the speed of frequency change specifically for each type of navigation system, and by that same means ensure they will operate in optimal fashion from the viewpoint of obtaining a potentially possible accuracy in determining position coordinates and components of the object's velocity vector.

The distinguishing features of the proposed method are:

Receipt by N-channel receivers of navigation radio signals of N satellites, one of the channels of which is the driving one, and the others, the driven ones.

Determination of the differences in range increments and differences in range by subtracting, from the measured phase increments, the carrier and time shifts of code sequences by driven receivers of phase increments of carrier and time shift of code sequences measured by the driving device.

Measurement of dual differences of range increments by separating signals with frequencies equal to Doppler frequency differences, received by the driving channel and each driven channel of the receiver, using quadrature phase detectors, to the first inputs of which driven channel signals arrive, and to the second inputs of which signals of the driven receivers arrive, and by multiplying their mean values by the measured interval.

Receipt by the driving channel of the receiver of radio signals of ground and air sources of radio emission and radio emission from spacecraft of other systems.

Use of driving channels of the receiver as a simulator signal.

Separation of signals with Doppler frequencies when receiving phase modeled signals with suppressed carriers by squaring them, with filtration and with subsequent return of the frequencies to the desired ones using frequency dividers.

Thus, the proposed method for determining positional coordinates and components of the objects' velocity vector by radio signals of SRNS spacecraft is novel and exhibits significant differences and, when used, provides a positive effect consisting in increasing accuracy, reliability and trustworthiness of navigation determinations of satellite and ground radio navigation systems.

What is claimed is:

1. Range finding method for determining the position and vector velocity components of objects by radio signals from spacecraft of satellite radio navigation systems, in which an N-channel receiver placed on the object receives radio navigation signals from satellites to determine range from the objects to each satellite by measuring time shifts of code sequences formed by satellite generators relative to code sequences formed by the object's generators, and also components of the velocity vector by means of measuring received Doppler shift frequencies using systems for tracking the carriers, characterized in that in the N-channel receiver, one of which is the driving one, and the other the driven channels, range differences are determined between ranges measured by the driven receivers and the range measured by the driving receiver, and also the velocity differences between range change rates are determined by computing according to measured Doppler frequency shifts by the driven receiver and range change rates computed according to measurements of the Doppler frequency shift by the driving receiver, then dual range differences and dual differences in range change rates are determined by means of mutually subtracting from each other of range differences and differences in range change rates.

2. Method according to claim 1, characterized in that range differences are determined by the driving and the driven receivers between the object and two satellite positions, being determined by a measured interval by means of measuring phase increments of the carriers with use of phase automatic frequency control of tracking systems of the carriers of satellite radio navigation signals.

3. Method according to claim 1, characterized in that the dual range differences between the object and two satellite positions, being determined by a measured interval, are determined by measuring Doppler frequency differences received by the receiver using

quadrature phase detectors, having multiplied their mean values by the measured interval.

4. Method according to claims 1 – 3, characterized in that the receiver of the driving channel receives signals of a simulator of satellite signals.

5. Method according to claim 3, characterized in that the signals with Doppler frequencies are separated by squaring the signals being received, with a subsequent return of the frequencies to the desired ones, using frequency dividers.

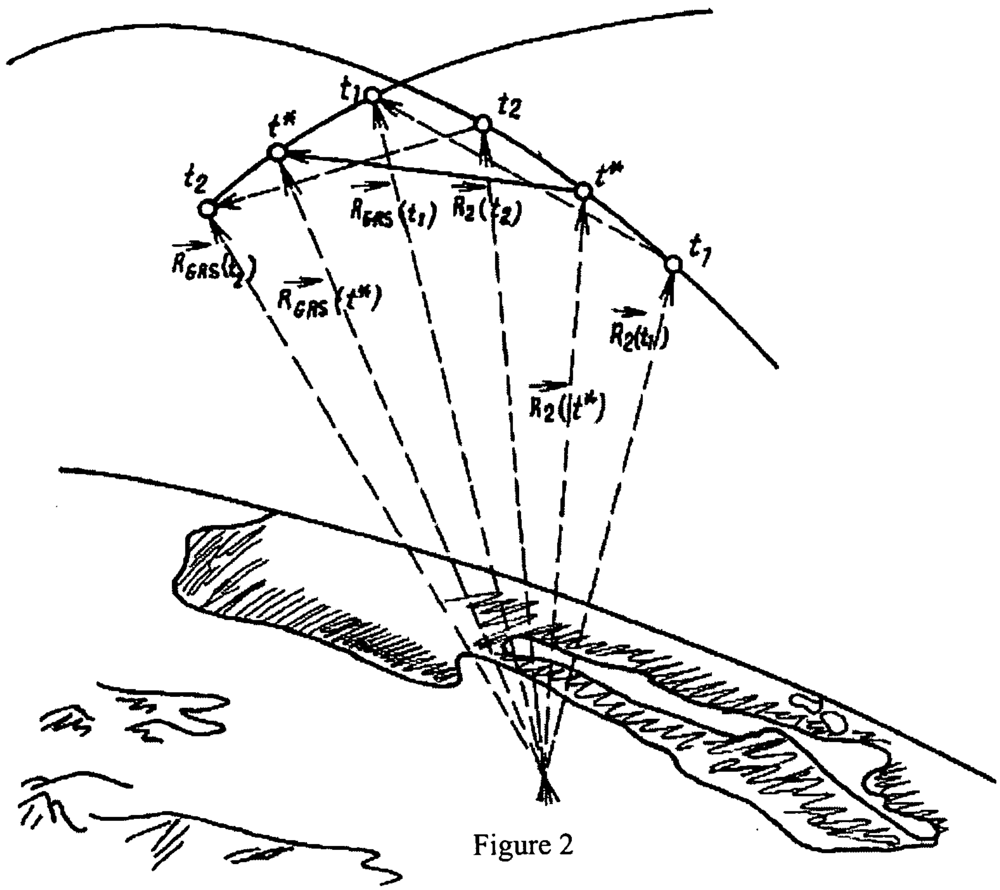
t_1
t_2
t^*
t_2
t^*
t_1
$\vec{R}_{GRS}(t_1)$
$\vec{R}_2(t_2)$
$\vec{R}_{GRS}(t_2)$
$\vec{R}_{GRS}(t^*)$
$\vec{R}_2(t_1)$
$\vec{R}_2(t^*)$

Figure 2

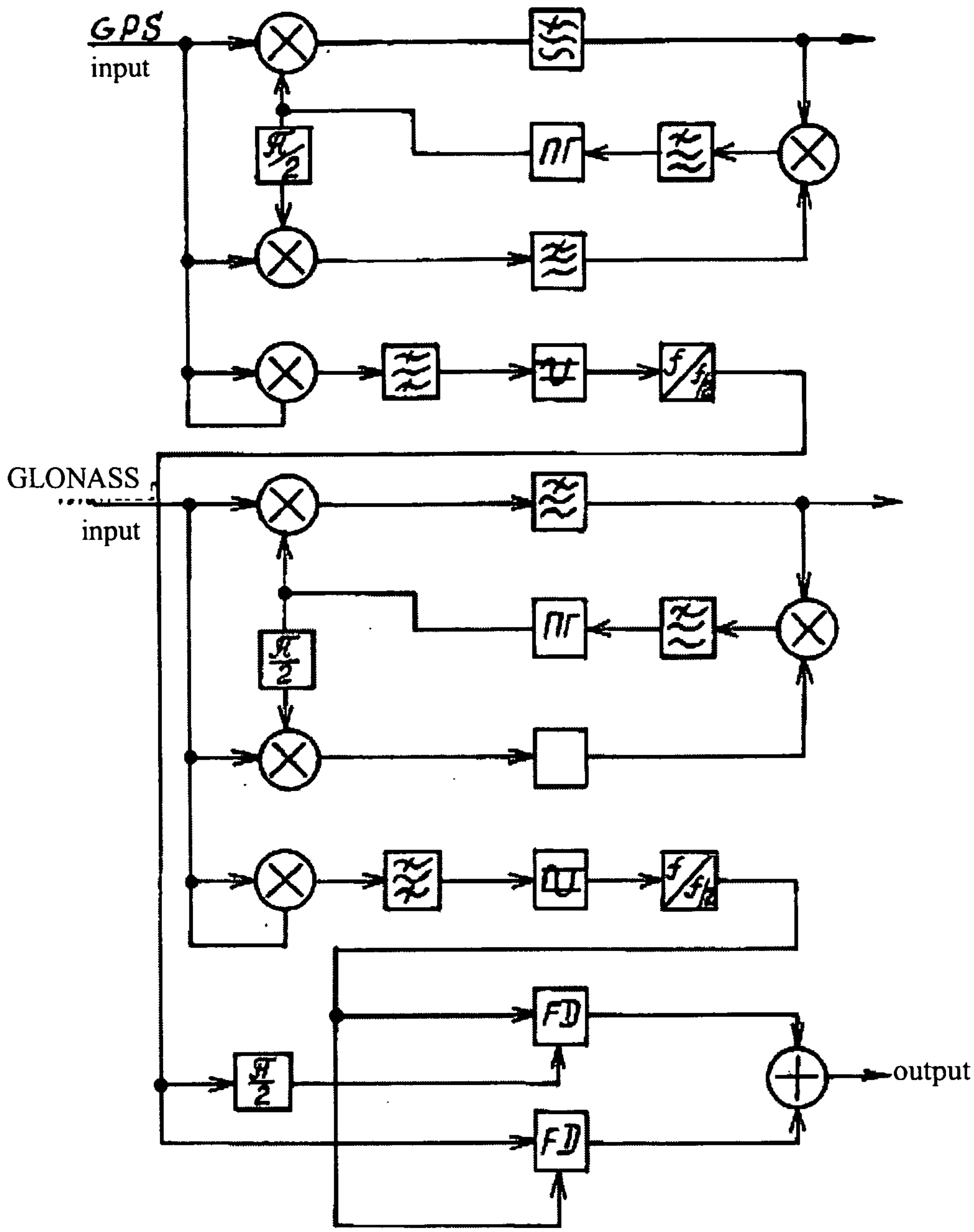

Figure 3